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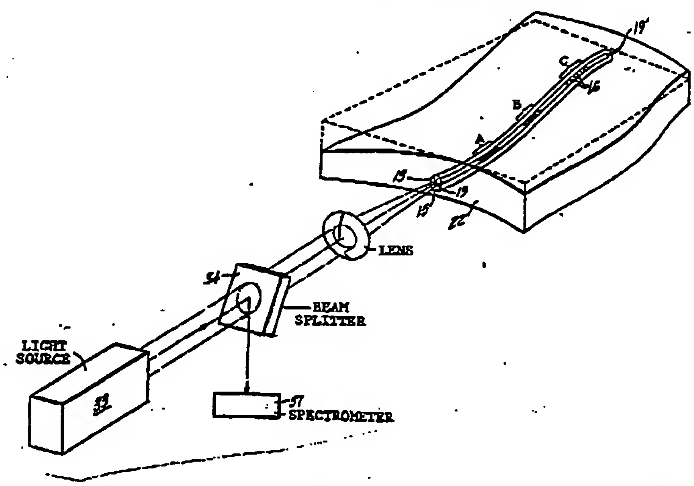
(54) Title: DISTRIBUTED, SPATIALLY RESOLVING OPTICAL FIBER STRAIN GAUGE



(57) Abstract

A distributed, spatially resolving optical fiber strain gauge (13) in which the core (19) of the optical fiber (15) is written with periodic grating patterns (16) effective for transmitting and reflecting light injected into the core (19). Spectral shifts in the transmitted and reflected light indicate the intensity of strain or temperature variations at positions of the grating (16) corresponding to the associated wavelength of injected light.

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Description

Distributed, Spatially Resolving Optical Fiber Strain Gauge

Technical Field

This invention relates to the establishment of phase gratings and the optical detection and measurement of strain distributions with multi-wavelength light provided to said phase gratings.

Background of the Invention

It is known to determine the distribution of axial strain or temperature along the length of a fiber optic sensor according to the technique described by S. K. Yao et al. in Volume 21 Applied Optics (1982) pages 3059-3060. According to this technique, very small deformations at the interface between an optical core and its cladding will cause light measurably to couple from core to cladding modes. This permits measurements by time-domain reflectometry or a series of cladding taps to determine transmission loss and the distribution of applied perturbations.

Disclosure of Invention

According to the invention, a strain sensor comprising an optical waveguide including a core for carrying light injected at selected wavelengths is impressed and reflected with one or more periodic

phase grating for modifying the reflection and transmission of injected light at the position of said grating in response to conditions of local physical or thermal strain.

Brief Description of the Drawing

Fig. 1 is a schematic drawing of the spatially resolving optical fiber strain gauge according to the invention addressed herein;

Figs. 2A through 2C are partial schematics of selected sections of the optical waveguide including its cores, indicating grating patterns of varying spacing corresponding to selected regions A, B and C in a mechanical structure being monitored for strain;

Fig. 3 is a graph of the intensity spectrum of the reflected light produced by injecting broadband light into the core of the waveguide with shifts in the spectral lines indicating strain at specific stations; and

Fig. 4 shows a schematic illustration of a technique for establishing a grating pattern of variable spacing at selected positions along the length of the optical waveguide.

Best Mode for Carrying Out the Invention

Fig. 1 shows a schematic diagram of the spatially resolving optical fiber strain gauge 13. The gauge 13 includes an optical waveguide 15 or fiber operative to transmit a single or lowest order mode of injected light.

The core 19 of waveguide 15 is preferably a Germanium-doped silica or glass filament. The core 15 contains a series of variable spacing Bragg reflection gratings 16 written, impressed or

otherwise applied by application of a variable two-beam ultraviolet (less than 300 nanometers) interference pattern. These periodic gratings 16 or refractive index perturbations are permanently induced by exposure to intense radiation.

Figs. 2A through 2C shows the establishment of different wavelength gratings 16 corresponding to respective locations on core 19.

Each of selected gratings 16 is formed by transverse irradiation with a particular wavelength of light in the ultraviolet absorption band of the core material associated with a position in a structural component 22. This procedure establishes a first order absorption process by which gratings 16 each characterized by a specific spacing and wavelength can be formed by illuminating core 19 from the side with two coplanar, coherent beams incident at selected and complementary angles thereto with respect to the axis of core 19. The grating period is selected by varying the selected angles of incidence. Thus, a permanent change in the refractive index is induced in a predetermined region of core 19, in effect creating a phase grating effective for affecting light in core 19 at selected wavelengths.

As indicated in Fig. 1 the optical waveguide 15 and core 19 are attached or embedded in a section of structural component 22, in particular a plate for example. Core 19 contains characteristic periodic refractive index perturbations or gratings 16 in regions A, B and C thereof. A broadband light source 33 or tunable laser is focused through lens 33' onto the exposed end of core 19. A beam splitter 34 serves to direct the return beam from core 19 toward

a suitable readout or spectrometer 37 for analysis. Alternatively, a transmitted beam passing out of the end 19' of core 19 could be analyzed.

The spectrum of the reflected light intensities from strain gauge 13 is shown in Fig. 3. A complementary spectrum is also established passing out of the end 19' of core 19. The spectrum contains three narrowband output lines centered at respective wavelengths: $lambda_A$, $lambda_B$ and $lambda_C$. These output signals arise by Bragg reflection or diffraction from the phase gratings 16 at respective regions A, B and C. In this example, regions A and C of structural component 22 have been strained by deformation, causing a compression and/or dilation of the periodic perturbations in the fiber core.

As a result, the corresponding spectral lines are shifted as shown in Fig. 3 to the dotted lines indicated. The respective wavelength differences delta $lambda_A$ and delta $lambda_C$ are proportional to strain in respective regions A and C.

Fig. 4 illustrates the formation of periodic perturbations or gratings 16 in a region of fiber core 19 in response to exposure of core 19 to intense transverse ultraviolet radiation. Grating spacings Δa and Δc are controlled by the incidence angle of incident interfering beams 99 and beam 101. As can be seen, the angles of incidence of beams 99 are complements (i.e. their sum equals 180 degrees) to each other with respect to the axis of core 19. The incident pair of beams 99 can be derived from a single incident beam 101 passing in part through a beam splitter 103 and reflecting from spaced parallel reflectors 105. By increasing the separation between reflectors 105 and correspondingly varying the angles

of incidence of beam 101, the angles of incidence of beams 99 upon core 19 can be controlled. Accordingly, the fringe spacing in grating 16 is varied as desired along the length of core 19, to permit a determination of strain or temperature corresponding to location along gauge 13.

Several spacings can be superimposed or colocated by this technique for the response set forth below.

Sensitivity to external perturbations upon structural component 22 and thus also upon core 19 depends upon the Bragg condition for reflected wavelength. In particular, the fractional change in wavelength due to mechanical strain or temperature change is:

$$d(\text{lambda}_i)/\text{lambda}_i = (q + \alpha)\Delta T + (1 + [\partial n/\partial \epsilon]/n)\epsilon$$

$$\simeq 8 \times 10^{-6}/^{\circ}C$$

$$+ 8 \times 10^{-7}/\text{microstrain, where:}$$

q is the thermooptic coefficient, which is wavelength dependent;

α is the expansion coefficient;

ϵ is the axial or longitudinal strain;

lambda_i is the wavelength reflected by the grating at location i along the core 19;

n is the refractive index of the optical waveguide; and

ΔT is the change in temperature.

This relationship suggests a way to compensate for temperature changes along the length of the fiber

sensor. In particular, if superimposed gratings of different spacings are provided, each of the two gratings will be subject to the same level of strain, but the fractional change in wavelength of each grating will be different because q is wavelength dependent.

Accordingly, each pair of superimposed gratings will display a corresponding pair of peaks of reflected or transmitted intensity. Accordingly, the shifts of these peaks due to a combination of temperature and strain can be subtracted. The shifts in these peaks due to strain will be the same in magnitude. Accordingly, any remaining shift after subtraction is temperature related. Thus, when it is desired to know the strain difference as between several locations possibly subject to a temperature difference, the temperature factor can be compensated.

The relationship therefore permits compensation for temperature variation during measurement, since the photoelastic and thermooptic effects are wavelength dependent. In other words, by superimposing two or more gratings at each location of interest, two or more spectral lines are established at each point of measurement. Strain will affect both lines equally; temperature will not. Thus, sufficient information is available to permit determination of the magnitude of strain and the temperature difference.

The information above is likely to cause others skilled in the art to conceive of other variations in carrying out the invention addressed herein, which nonetheless are within the scope of the invention.

Accordingly, reference to the claims which follow is urged, as those specify with particularly the metes and bounds of the invention.

Claims

1. A strain sensor comprising an optical waveguide including a core for guiding light through a selected path in a mechanical structure subject to strain, and an optical source for injecting broadband light into said core of the optical waveguide, said core being characterized in that it is impressed with a plurality of periodic gratings that modify the reflection and transmission of the injected broadband light at positions of said gratings under conditions of local strain or temperature variation.

2. The strain sensor of claim 1, further characterized in that said strain sensor includes means for analyzing shifts in the spectrum of said reflected and transmitted of broadband light to determine the magnitude and location of strain in said mechanical structure.

3. The strain sensor of claim 1, further characterized in that each grating location is impressed with gratings of at least two different wavelengths, whereby temperature and strain variations can independently be determined.

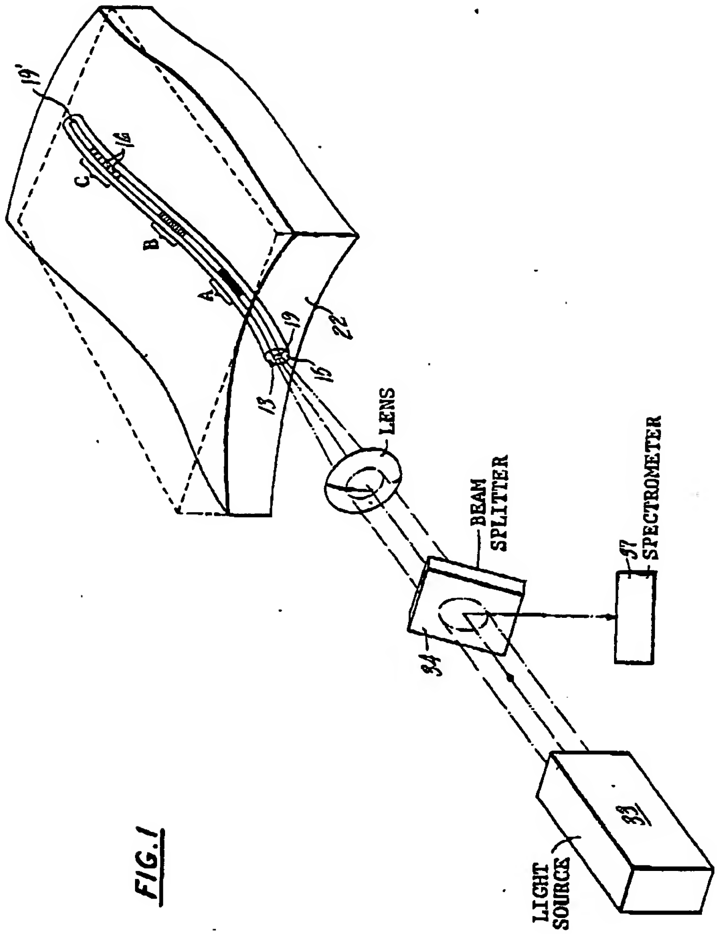

19'
16
C
B
A
19
22
13
15
LENS
BEAM SPLITTER
94
97
SPECTROMETER
LIGHT SOURCE

FIG.1

FIG. 2A

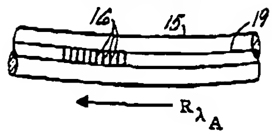


FIG. 2B

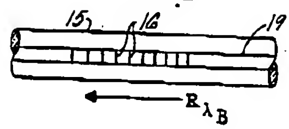


FIG. 2C

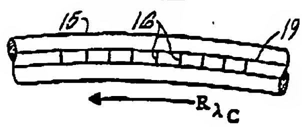
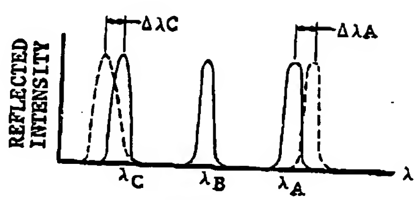
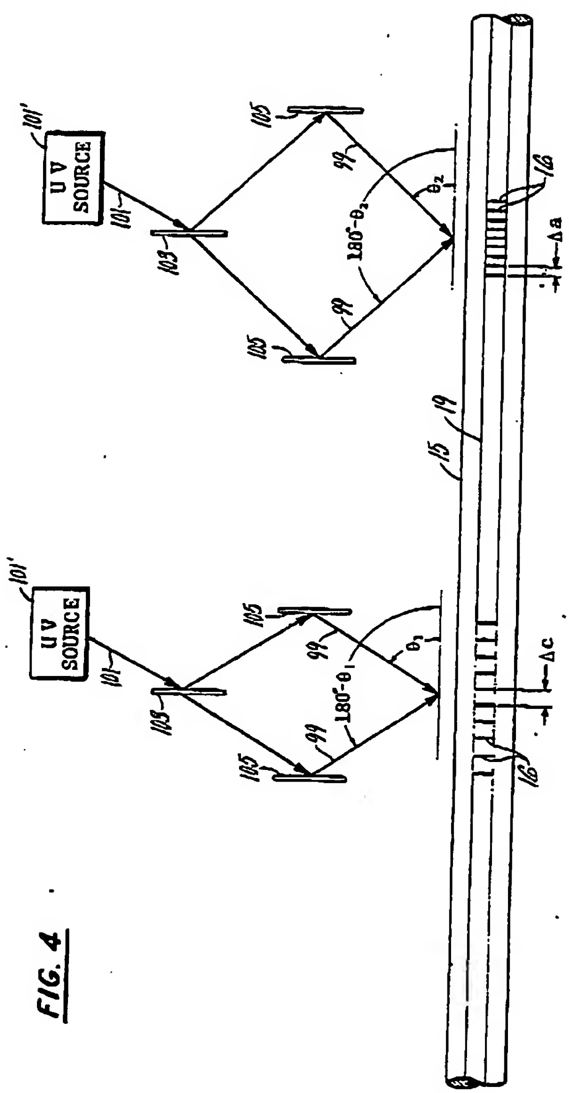


FIG. 3





U V SOURCE
101'
101
103
105
99
$180°-\theta_2$
θ_2
16
Δa
19
15
U V SOURCE
101'
101
103
105
99
$180°-\theta_1$
θ_1
Δc
16

FIG. 4

INTERNATIONAL SEARCH REPORT

International Application No PCT/US85/01450

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

INT CL[4] G01B 11/16; G01J 5/08, 5/38
US CL 356/32, 44

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols	
US	356/32, 44 250/227 73/800	350/96.15, 96.19

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
X	US, A, 4,268,116 (SCHMADEL ET AL) 19 MAY 1981	1, 2
Y	US, A, 4,400,056 (CIELO) 23 AUGUST 1983	1-3

* Special categories of cited documents: [15]
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IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
02 OCTOBER 1985	07 OCT 1985
International Searching Authority [1]	Signature of Authorized Officer [20]
ISA/US	Vincent P. McGraw VINCENT P. McGRAW

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